# OPTIMAL SPEED AND TORQUE ESTIMATION FOR IMPROVING THE DTC DYNAMIC PERFORMANCE OF INDUCTION MACHINES

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**DEDICATION**

*To my beloved parents, wife, sons, brothers and sisters*

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# ABSTRACT

High-performance AC drives require accurate speed, flux, and torque estimations to provide a proper system operation. Thus, this thesis proposes a robust observer, i.e. Extended Kalman Filter (EKF), to offer optimal estimations of these components in order to improve the dynamic performance of Direct Torque Control (DTC) of induction motor drives. The selection and quality of EKF covariance elements have a considerable bearing on the effectiveness of motor drives. Many EKF-based optimization techniques involve only a single objective for the optimal estimation of speed without giving concern to the other variables. In addition, the optimization is performed on a complicated EKF structure. Nevertheless, in this study, both speed and torque are concurrently estimated. The work presents a new method to investigate the selection of EKF filters by using a Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) developed for resolving problems with multi-objectives. Filter element selection is the process of improving the concurrent estimation of speed and torque in order to increase EKF accuracy and allow higher drive efficiency. The proposed multi-optimal EKF-based estimation observer is used in combination with the sensorless direct torque control of induction motor. The investigated results for the multi-objective optimization indicate that the speed optimization gives superior performance when compared to the optimal torque. Owing to the large computation time of EKF algorithm, it increases the sampling time of DTC which leads to an increase in the motor torque ripples. The thesis proposes a Constant Frequency Torque Controller (CFTC) to replace the hysteresis torque controller that offers constant switching frequency and reduces torque ripples. Moreover, the CFTC has the capability of continuous switching regardless of speed variation; hence, leading to a consistent rotation of flux. Consequently, improvement on speed estimation, particularly at low and zero speed regions is accomplished and enhancement on the dynamic performance of torque is achieved when the reference speed change is applied from 0 rad/s, on the condition that the EKF observer is accurately optimized. To verify the improvements of the proposed methods, simulation and experimentation as well as comparison with the EKF-based DTC with the hysteresis controller are carried out.

# ABSTRAK

Pemacu AC berprestasi tinggi memerlukan kelajuan yang tepat, fluks dan jangkaan tork bagi menyediakan suatu operasi sistem yang baik. Maka, tesis ini mencadangkan satu pemerhati yang teguh seperti Penapis Lanjutan Kalman (EKF), untuk menawarkan jangkaan optima komponen ini untuk memperbaiki prestasi dinamik sesuatu Kawalan Tork Langsung (DTC) pemacu motor aruhan. Pemilihan dan kualiti elemen-elemen kovarian EKF mempunyai pengaruh yang besar ke atas keberkesanan pemacu motor. Banyak teknik pengoptimasi berasaskan EKF melibatkan hanya satu objektif tunggal bagi jangkaan optima kelajuan tanpa mengambil kira pembolehubah lain. Tambahan pula, optimasi dijalankan ke atas struktur EKF yang rumit. Tetapi, dalam kajian ini kelajuan dan tork kedua-duanya dianggarkan secara serentak. Kajian membentangkan satu kaedah baru untuk menyelidik pemilihan penapis-penapis EKF dengan menggunakan Algoritma-II Genetik Pengisihan Bukan Dominan (NSGA-II) yang dibangunkan bagi menyelesaikan masalah berkaitan pelbagai objektif. Pemilihan elemen penapis ialah proses memperbaiki jangkaan serentak kelajuan dan tork untuk meningkatkan ketepatan dan meninggikan lagi keberkesanan. Pemerhati jangkaan pelbagai optima berdasarkan EKF diguna bersama dengan pengawalan tork langsung motor aruhan tanpa sensor. Keputusan kajian bagi optimasi pelbagai objektif menunjukkan optimasi kelajuan memberi prestasi lebih baik dibandingkan dengan tork optima. Disebabkan tempoh pengiraan yang lama bagi algoritma EKF, ia meningkatkan masa sampel DTC yang membawa kepada peningkatan dalam riak tork motor. Tesis ini mencadangkan satu Pengawal Frekuensi Tork Tetap (CFTC) untuk menggantikan pengawal tork histerisis yang menawarkan frekuensi pertukaran tetap dan mengurangkan riak tork motor. Disamping itu, CFTC berupaya membuat pertukaran berterusan tanpa menghiraukan perbezaan kelajuan; maka, ini membawa kepada satu putaran fluks yang konsisten. Oleh itu, peningkatan dalam jangkaan kelajuan, khasnya pada bahagian kelajuan rendah dan sifar dicapai dan kemajuan prestasi dinamik tork diperolehi apabila perubahan kelajuan rujukan dihasilkan bila perubahan kelajuan rujukan diaplikasikan daripada 0 rad/s, dengan syarat pemerhati EKF dioptimakan secara tepat. Bagi mengesahkan penambahbaikan kaedah-kaedah yang disyorkan, simulasi dan eksperimen serta perbandingan dengan DTC berdasarkan EKF dengan pengawal histerisis telah dijalankan.

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| | | |
|---|---|---|
| *AC* | - | Alternating Current |
| *ADC* | - | Analog to digital converter |
| *B* | - | Input matrix |
| *BPF* | - | Band pass filter |
| *CFTC* | - | Constant Frequency Torque Controller |
| $C_{lower}$ | - | Lower triangular carrier |
| $C_{p\text{-}p}$ | - | Peak to peak value of the triangular carrier |
| $C_{upper}$ | - | Upper triangular carrier |
| *d,q* | - | Direct and quadrature axis of the stationary reference frame |
| *DAC* | - | Digital to analog converter |
| *DC* | - | Direct Current |
| *DSP* | - | Digital Signal Processor |
| *DTC* | - | Direct Torque Control |
| $d^{\psi_s}$, $q^{\psi_s}$ | - | Direct and quadrature axis of the estimated stator flux reference frame |
| *EKF* | - | Extended Kalman filter |
| *emf* | - | Electromotive force |
| $f_c$ | - | Carrier frequency |
| *FOC* | - | Field Oriented Control |
| *FPGA* | - | Field Programmable Gate Array |
| *I.E* | - | Incremental Encoder |
| *I.M* | - | Induction Machine |
| $i_{rd}$, $i_{rq}$ | - | d and q components of the rotor current in stationary reference frame |
| $i_s$, $i_r$ | - | Stator and rotor current space vectors in stationary reference frame |
| $i_{sd}$, $i_{sq}$ | - | d and q components of the stator current in stationary reference frame |
| $i_s^g$ , $i_r^g$ | - | Stator and rotor current space vectors in general reference frame |
| *J* | - | Moment of inertia |
| *KF* | - | Kalman filter |
| $k_i$ | - | Integral gain of the PI controller |
| $k_p$ | - | Proportional gain of the PI controller |

| | | |
|---|---|---|
| $L_m$ | - | Mutual inductance |
| *LPF* | - | Low pass filter |
| $L_r$ | - | Rotor self-inductance |
| $L_s$ | - | Stator self-inductance |
| *MRAS* | - | Model reference adaptive system |
| *P* | - | Number of pole pairs |
| *p.p.r* | - | Pulse per revolution |
| *PI* | - | Proportional - Integral |
| *PWM* | - | Pulse Width Modulation |
| *PWM* | - | Pulse-width modulation |
| *r.m.s* | - | Root mean squared |
| $R_s$, $R_r$ | - | Stator and rotor resistance |
| $S_a$, $S_b$, $S_c$ | - | Switching states of phase a, b, c |
| *SI* | - | Signal injection |
| *SMO* | - | Sliding mode observer |
| *SNR* | - | Signal to noise ratio |
| *SVM* | - | Space Vector Modulation |
| $T_c$ | - | Output of PI controller for the CFTC |
| $T_e$ | - | Electromagnetic torque |
| $T_{e,rated}$ | - | Torque rated |
| $T_{e,}^{ref}$ | - | Reference torque |
| $T_{stat}$ | - | Torque error status |
| $t_{tri}$ | - | Period of $C_{upper}$ or $C_{lower}$ |
| $u$ | - | Control-input vector |
| $V_{DC}$ | - | DC link voltage |
| *VFD* | - | Variable frequency drives |
| *VHDL* | - | VHSIC hardware description language |
| $v_s$ | - | Stator voltage space vector in stationary reference frame |
| *VSD* | - | Variable speed drives |
| $v_{sd}$, $v_{sq}$ | - | d and q components of the stator voltage in stationary reference frame |
| $v_s^g$ | - | Stator voltage space vector in general reference frame |
| *VSI* | - | Voltage Source Inverter |
| $\delta_{sr}$ | - | Difference angle between stator flux linkage and rotor flux linkage |
| $\theta_r$ | - | Angle with respect to rotor axis |
| $\theta_s$ | - | Angle with respect to stator axis |
| $\sigma$ | - | Total flux leakage factor |
| $\tau_r$ | - | Rotor time constant |
| $\Psi_s$ | - | Estimated stator flux linkage |

| | | |
|---|---|---|
| $\Psi_s{}^g$, $\Psi_r^g$ | - | Stator and rotor flux linkage space vectors in general reference frame |
| $\Psi_s$, $\Psi_r$ | - | Stator and rotor flux linkage space vectors in stationary reference frame |
| $\Psi_{sd}{}^{\psi s}$, $\Psi_{sq}{}^{\psi s}$ | - | d and q components of stator flux in stator flux reference frame |
| $\Psi_{sd}$, $\Psi_{sq}$ | - | d and q components of stator flux in stationary reference frame |
| $\omega_e$ | - | Steady state synchronous frequency in rad./s |
| $\omega_m$ | - | Rotor mechanical speed in rad./s |
| $\omega_r$ | - | Rotor electrical speed in rad./s |
| $\omega_{slip}$ | - | Steady state slip frequency in rad./s |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview of Induction Motor Drives

Induction motors (IMs) dominate the world market (more than 85% of electrical motors)[1] with broad applications in industries, public services and household electrical appliances [2-3]. The popularity of IMs is mainly due to their low cost, ruggedness, high reliability, and minimum maintenance [4]. The induction machines began to gradually replace DC machines in many industrial applications as the Field Oriented Control (FOC) introduced by F. Blachke in 1970's can produce comparable performance to that obtained in DC machines [5]. Moreover, their popularity is also assisted by the rapid development in power semiconductor devices and the emergence of high-speed microprocessor and digital signal processors [6].

Much of the previous research has been devoted to improving the drive systems of the IM, especially the control methodology. The advent of power semiconductor switches and digital control technology has led to remarkable improvements in the variable frequency drives (VFDs) i.e. providing smoother speed tuning, greater motor control, and fewer energy losses. Based on the torque and speed control techniques, the IM-VFDs can be classified into two main categories namely the scalar and vector control methods, as illustrated in Figure 1.1. A brief discussion on these control methods are given as follows.

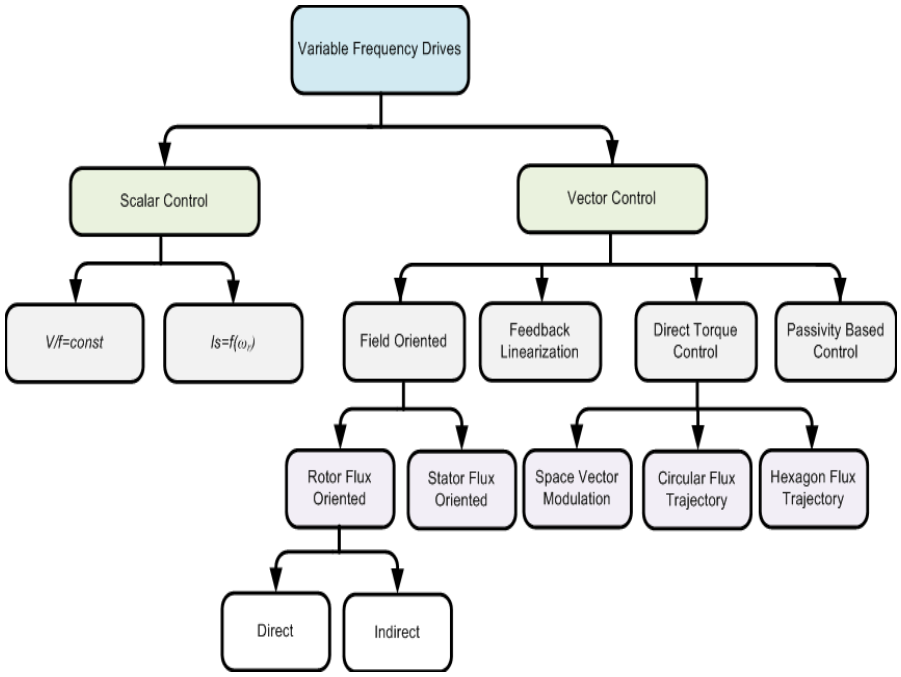


**Figure 1.1** Classification of variable frequency drives for IM control [7]

### 1.1.1 Scalar Control

Scalar control is a simple control technique used to control the speed of complex and nonlinear behavior of the IMs based only on magnitude and frequency of the applied voltages. The control is developed based on a per phase steady-state equivalent circuit of the IM with an objective of maintaining the magnetizing current constant by changing the magnitude of applied voltage proportional to the applied frequency. The magnitude and frequency needed to maintain this constant magnetizing current is then synthesized using a voltage source inverter. An example of a scalar control of IM which is based on a constant ratio of applied voltage to the frequency, widely known as the constant volts per hertz (or constant V/f), is shown in Figure 1.2. For this particular example of control scheme, the speed is controlled in a closed loop manner by measuring the actual speed using a speed sensor. As shown in the figure, the difference between the reference rotor speed value, $\omega_r^r$, and the actual rotor speed, $\omega_r$ , which is speed error, is tuned via the conventional

proportional-integral (PI) controller, and a limiter to obtain the slip-speed reference $\omega_{sl}{}^{r}$. Then, the slip-speed reference and electrical rotor speed are added together to generate the fundamental stator frequency reference. Thereafter, the fundamental stator frequency reference determines the amplitude of the fundamental stator voltage reference, $V_s^r$. Without the speed feedback (i.e. open loop constant V/f), the speed regulation will be poor and heavily depends on the mechanical load; nonetheless, for some non-critical applications this is good enough. The inclusion of the speed sensor will increase overall cost of the drive system, but yet the system is still not suitable to be used for applications where precise torque control is mandatory; scalar control is incapable of controlling the most essential variables in IMs, i.e. torque and flux [8]. The main drawbacks of this technique are the unsatisfactory speed accuracy, especially at the low speed regions, and poor torque response. The reaction of the motor to the applied frequency and voltage governs motor flux and torque indirectly based on the steady-state model of the IM [7] which is not valid in transient state. Therefore, for applications requiring precise torque control, vector control schemes are normally adopted as discussed in the next section.

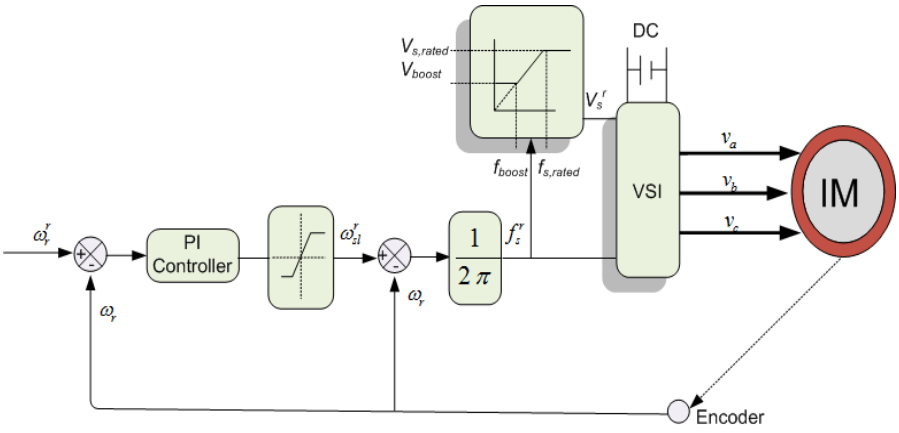


**Figure 1.2** Closed loop IM with constant V / Hz variable frequency drive

### 1.1.2 Field Oriented Control (FOC)

Field oriented control (FOC) or vector control (VC) was introduced by Hasse and Blaschke from Germany, in 1969 and 1971 respectively [7]. On the contrary to the scalar control, the development of FOC control scheme is based on dynamic model of the IM where the voltages, currents and fluxes are expressed in space vector forms. The representation of the motor's quantities using space vectors valid under both steady state and transient conditions hence with FOC, excellent transient response can be achieved. The rotor flux FOC scheme is based on the frame transformation of all quantities to a rotating frame fixed to the rotor flux. In this rotating rotor flux frame, all quantities rotating at synchronous speed will appear as DC quantities. If the flux is aligned to the d axis of this reference frame, it can be shown that the d and q components of the stator current represent the flux and torque component respectively. This means that utilizing FOC, the control of IM is transformed to a simple control scheme similar to the DC motor control where the torque and flux components are decoupled. The way the rotor flux position is obtained determines the type of FOC as either direct FOC or indirect FOC. In indirect FOC, the flux position is obtained by adding the slip position to the measured rotor position, whereas in direct FOC it is calculated (or can also be measured) based on the terminal variables and rotor speed. Figure 1.3 shows the block diagram of a direct rotor flux FOC with speed loop. The rotor speed, which is obtained from the encoder, is used as the speed feedback and also more importantly is used by the observer to calculate the rotor flux position. Alternatively, instead of rotor flux orientation, it is also possible to perform the orientation to the stator flux – which is known as stator flux FOC. It can be seen that in FOC scheme, the knowledge of rotor position need to be acquired accurately in order to perform the frame transformation. Inaccurate rotor flux position causes the torque and flux not to be completely decoupled and consequently resulted in deterioration in the torque dynamics [9].

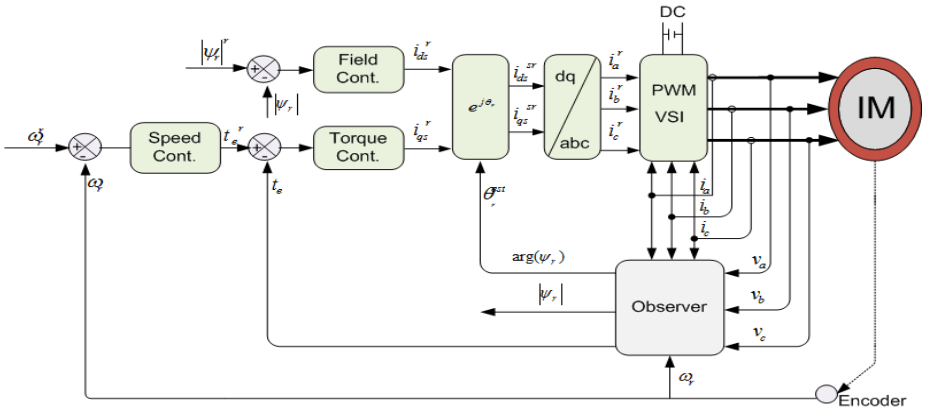


**Figure 1.3** Fundamental direct FOC technique with an observer used for rotor flux estimation

### 1.1.3 Direct Torque Control (DTC)

DTC has become significantly popular and can be considered as an alternative controller to the well-known FOC scheme due to its excellent torque response and its simple control algorithm [10],[11]. The basic structure of DTC of IM scheme is shown in Figure 1.4. The DTC scheme, as initially proposed in [10], consists of a pair of hysteresis comparators, torque and flux calculator, a lookup table, and a voltage-source inverter. The control structure of DTC is much simpler than the FOC system due to the absence of frame transformer, pulse width modulator, and a position encoder. The decouple control of torque and flux is established by selecting appropriate voltage vectors to maintain the torque and flux errors within their hysteresis bands[10]. In DTC, the accuracy of the estimated stator flux is important to ensure correct voltage vector is selected for a decoupled torque and flux control. In its basic configuration, DTC scheme does not require rotor speed information since the estimation of stator flux is performed using voltage-model based observer. However, in order to improve the stator flux estimation at low speed, current-model based observer is normally used, which inevitably require the rotor

speed information. Even if stator flux estimation is performed totally based on voltage-model, the rotor speed is still needed for a speed control system. In other words, rotor speed is one of the important parameters that need to be either measured or estimated to ensure proper DTC scheme implementation. Two of the major issues which are normally addressed in DTC drives are the variation of the switching frequency of the inverter used in the DTC drives with operating conditions and the high torque ripple. It is well known that the source or root to the variable switching frequency problem is the use of hysteresis comparators, in particular, the torque hysteresis comparator [11]. To solve these problems, various implementation schemes are proposed. These include the use of predictive control scheme [12],[13], space vector modulation (SVM) technique [14], artificial intelligence (AI) [15] and constant switching controller [11].

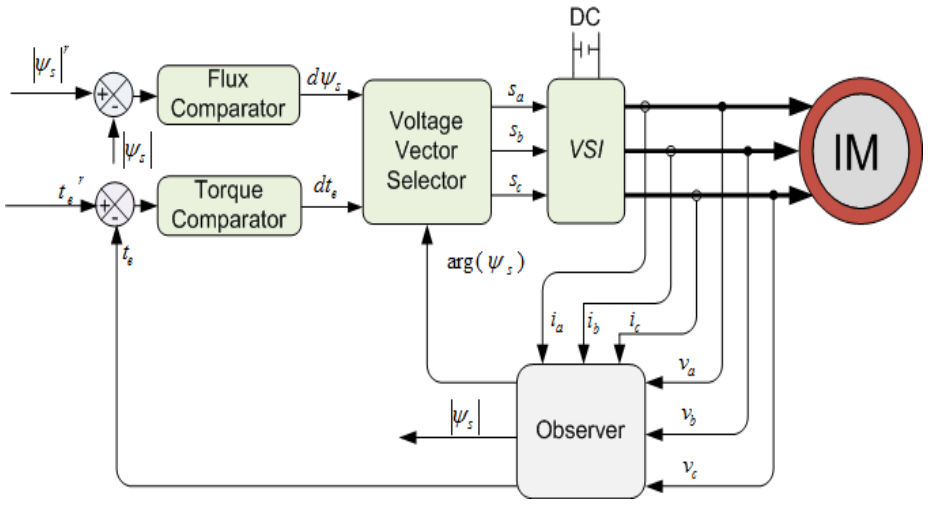


**Figure 1.4** Basic DTC scheme with an observer used for stator flux estimation

## 1.2 Sensorless Control Strategies

Based on the above discussions, regardless of the control strategies used, speed measurement is something essential for control algorithm and/or speed control in the IM drive. The motor speed can be measured using tachometer or optical encoder. However, mechanical speed sensors are associated with several

disadvantages: The increased in the size and cost of the drive system, reduced reliability and robustness, and regular maintenance of the speed sensor itself. Furthermore, in some applications, it is inappropriate to install the mechanical speed encoder at the motor shaft due to the physical and environment constraints. Accordingly, increasing attempts have been made to eliminate the encoder mounted at the motor shaft without affecting the performance of the VFD system. Hence, research interests on sensorless techniques applied to IMs have grown dramatically in the last few decades. Generally, the speed estimation techniques can be classified into two broad categories: Estimation based on mathematical machine model and estimation through signal injection to exploit the anisotropy of the machine as will be discussed in Chapter 2.

## 1.3 Thesis Objectives and Contributions

The objective of this thesis is to develop a robust estimation method and improve the performance of the speed sensorless DTC of induction motors for a wide speed region, particularly persistent operation at and around zero speed. Despite the improvements, the proposed techniques also aim to retain the simple control structure of DTC drive. The thesis utilizes the simplicity of DTC to propose and implement a powerful estimation technique of extended Kalaman filter (EKF) to achieve a proper induction machine control employed in the DTC with a hysteresis controller (for convenience, it is recognized as EKF-based DTC-HC) and DTC with a constant frequency torque controller (for convenience, it is identified as EKF-based DTC-CSFC) of induction machine i.e. to achieve a speed sensorless drive system, to improve torque dynamic control, and to enhance speed estimation capability for a wide speed operation. While doing the research, the thesis makes the following contributions.

1) It offers an alternative method in tuning the EKF for the estimation application of the squirrel cage IM. The main motivation is to reduce the EKF structure complexity by eliminating unnecessary covariance matrices

as well as widening the time scale for the optimization process. Application of the non-dominated sorting genetic algorithm II (NSGA II) method will be carried out to investigate the optimization performance of estimated torque besides the speed estimation. Indeed, this gives a systematic approach in selecting filter solutions with known minimum squared errors (MSEs) for the comparison purpose.

2) It analyses the effect of low and zero speed operation on the performance of speed and torque in EKF-based DTC-HC and EKF-based DTC-CSFC drives. Although the DTC is well established to give a high performance torque control, there is still room to further improve the performance based on the observation of the analysis.

## 1.4 Scope of Research

In order to achieve the objective of the research, the following scope of work has been carried out:

A critical and comprehensive review of speed estimation methods. In this review, the previous works on speed estimation methods used for induction machine drives are addressed. Their strengths and drawbacks based on several evaluation factors are highlighted. Besides giving the overview on the existing estimation methods, the objective of the review is to look for a gap in the literature, particularly on the issue of estimation at low speed region.

Modeling and simulation of the sensorless EKF-based DTC drive. In order to accurately study the sensorless EKF-based DTC of IM, a good model of the induction machine along with the proposed sensorless drive system is required. Thus, the parameters of equivalent circuit of IM are extracted by testing motor under no-load and locked rotor tests. A simple, fast and accurate modeling of overall system is then developed with the usage of MATLAB/SIMULINK software package.

Development of a simple and fast platform to optimize EKF parameters. The EKF was coded in MATLAB instead of using SIMULINK blocks where more time needs to be consumed. Thus, larger time scale has been used to improve on the optimization process.

The proposed speed estimation scheme utilizing a DTC drive have been verified and evaluated for its feasibility and effectiveness through simulation and hardware implementation. A processor and field programmable gate array devices (DS1104 and Xilinx FPGA (Baysis2)) were used to implement the DTC drive including the speed estimation strategy. A standard induction machine with suitable loads and IGBT-based VSI had been used for this purpose.

## 1.5 Organization of the Thesis

This thesis is organized into seven chapters. Their contents are outlined as follows:

**Chapter 2** describes the mathematical modeling of induction machine. Moreover, it provides an extensive review of speed and parameter adaptation techniques. In this review, the recent development of estimation strategies are reviewed based on two categories; mathematical machine model method and estimation via signal injection strategy.

In **Chapter 3,** the basic principle of DTC of induction machines and the state estimator using EKF observer are introduced. It first describes the main components that make the structure of DTC followed with the conventional method (low pass filter) for estimation flux and torque. For the sensorless IM drive, the speed of the motor must be estimated and not measured. Therefore, the EKF algorithm is introduced and discussed**.**

**Chapter 4** presents the optimization process of the EKF based-DTC-CSFC. At the beginning of the chapter, some background materials on the NSGA II and its application on EKF optimization are addressed. Simulation and experimental results on the proposed method are then presented.

**Chapter 5** will look at the effect of implementation of EKF on the performance of the DTC-HC and DTC-CSFC for speed estimation at wide speed, including a zero speed region. A quick procedure to design a proper controller of CFTC is presented. Based on the observation, EKF-based DTC-CFTC is able to produce a persistent and stable zero speed operation. Simulation and experimental results are presented to show the effectiveness of the proposed method.

**Chapter 6** describes the laboratory experimental set-up to implement the EKF-based DTC. The implementation of the tasks using DS1104 and Xilinx FPGA (Baysis2) are given. Detailed descriptions of each hardware components are provided.

**Chapter 7** gives the conclusion of the thesis. Several suggestions are given for possible directions of future work.

the proposed EKF-based DTC-CSFC can give superior dynamic performance when there is a step change from a zero speed zone to higher speed regions. Furthermore, the proposed speed sensorless DTC drive was capable of reducing torque ripple and producing constant switching frequency. The effectiveness of the proposed EKF-based DTC-CSFC in providing wider speed estimation and higher torque capability was verified by simulations and experiments as well as the comparison with the EKF-based DTC with the hysteresis torque controller.

The challenge for EKF experimental implementation is the derivation of the Jacobian matrices which require sufficiently small time intervals for linearization. In order to achieve small step intervals, some of the main tasks of the DTC (i.e. look-up table and blanking time) are implemented utilizing a Xilinx FPGA (Baysis2), this way; the DSP (DSPACE 1104) is able to execute the EKF-based DTC algorithm including the CSFC at the minimum sampling period of 120 μs.

## 7.2 Future Work

In this thesis, several contributions are presented. However, there remain potentially new findings in the area of EKF optimization and EKF-based DTC control that can still be explored. These can be summarized in the following section.

a) **Incorporating the parameter compensation.** In spite of the robustness of the EKF filter against parameter variations, the robustness comes to an end at a certain value. Therefore, it is suggested to incorporate parameter adaptation to compensate for the parameter variation which leads to more stability of the proposed drive system.

b) **Performing the CFSC and flux hysteresis calculation in the FPGA.** The triangular waveforms for the proposed CSFC are generated by the DSPACE 1104 with a sampling period of 120 μs.

Since the triangular waveform is generated by software, its frequency and the torque loop bandwidth are restricted by the sampling time of the DSP controller. Enlargement of the triangular frequency can be achieved if the CFSC is performed in the FPGA with higher frequency leading to great reduction of torque ripple. In addition, this can enhance the linearization of Jacobian matrices of EKF by achieving smaller step intervals; hence, enhancing the stability of EKF and improving the estimation of flux, torque, and speed.

c) **Replacing the hysteresis based flux controller with a fixed switching frequency controller.** In this thesis, the proposed method only utilizes the CSFC for the torque loop. In order for the stator flux error switching to be independent of the speed variation, it is suggested to replace the flux hysteresis comparator of DTC with CSFC.

d) **Applying other multi-objective swarm and evolutionary optimization techniques for EKF filter tuning.** In the current work, non-dominated sorting genetic algorithm II (NSGA II) was used to optimize the EKF filter parameters for speed and torque estimations. However, there are still other multi-objective techniques that have not been exploited for EKF tuning purpose. It would be exciting to explore the optimization capabilities of other techniques and then to be compared with NSGA II. Additionally, multi-objective can be applied not only for speed and torque, but can be used for speed and stator and rotor resistor optimization.

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